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Evaluation of Thermal Striping Phenomena at a Tee Junction of LMFR Piping System with Numerical Methods(II), Thermomechanical Calculations

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Abstract

Structural analysis has been conducted concerning a tee junction of the PHENIX secondary circuit due to thermal striping phenomena. Under the boundary condition provided from thermohydraulic analysis with DINUS-3, BEMSET and AQUA codes, possibility of crack initiation and its propagation were assessed by thermomechanical analysis. According to the calculated results, no crack was predicted to initiate at base metal portions, however, crack initiation and propagation through the pipe wall was estimated at the welded joint within 90,000 hours operation of the reactor.

1. Introduction

At an incomplete mixing area of high and low temperature fluids near the surface of a structure, temperature fluctuation of fluid gives thermal fatigue damage to wall structures. This coupled thermohydraulic and thermomechanical phenomenon is called thermal striping. An actual thermal striping problem at a tee junction of the PHENIX secondary circuit (Fig.1) was studied in the framework of the IAEA coordinated research program on "Harmonization and validation of Fast Reactor thermomechanical and thermohydraulic codes and relations using experimental data" [1]. A small pipe is attached to a main pipe of the PHENIX secondary circuit containing cold sodium at 340℃, and discharges hot sodium at 430℃ into the main pipe. The two convergent flows with different temperatures (Δ T=90K) are therefore mixed at the tee junction area. At the circumferential welded joint which locates at 160mm down stream from the tee junction, through wall cracks have been observed during the course of a campaign of inspection after operation of 90,000 hours. Possibility of crack initiation and its propagation around the mixing area were assessed, by using structural analysis codes under thermal boundary conditions obtained from thermohydraulic analysis with computational fluid dynamics (CFD) codes[1].

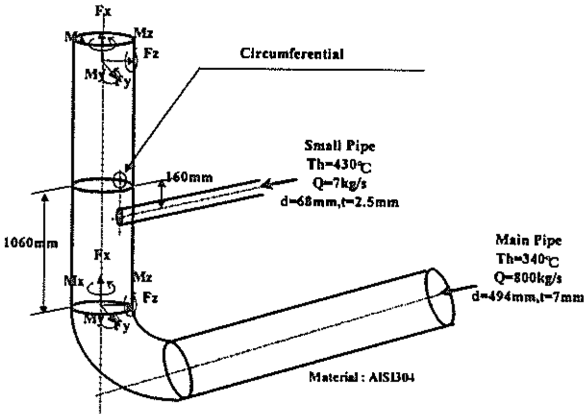

Fig. 1 Characteristics of the Phenix secondary piping system

2. Thermal striping problem and evaluation procedure

2.1 Problem definition and factors to be considered

In order to define complex thermal striping problem, which covers both thermohydraulic and thermomechanical fields, the author has divided this phenomenon into the following steps (Fig.2), i.e.: (1)temperature fluctuation in turbulent flow, (2)temperature fluctuation in boundary layer, (3)temperature fluctuation on structural surface, (4)temperature fluctuation inside structure, (5)high cycle fatigue crack initiation, and (6)high cycle fatigue crack propagation.

Through the discussion at the IAEA coordinated research program, several factors were found to cause the scatter of evaluation results. Among them, this study paid attention to the following factors, since structural integrity was sensitive to them.

(a) Attenuation of temperature fluctuation amplitude on steps (1) through (4) which consists of sub-factors: ①turbulent mixing, ②molecular diffusion, ③non-stationary heat transfer, and ④ thermal unloading

(b) Strength reduction on step (5) which consists of sub-factors; ⑤weldment, ⑥surface finish, and ⑦aging

(c) Effect of mean stress on steps (5) through (6) which consists of sub-factors: ⑧inner pressure and thermal expansion, ⑨hot spot, and ⑩weld residual stress

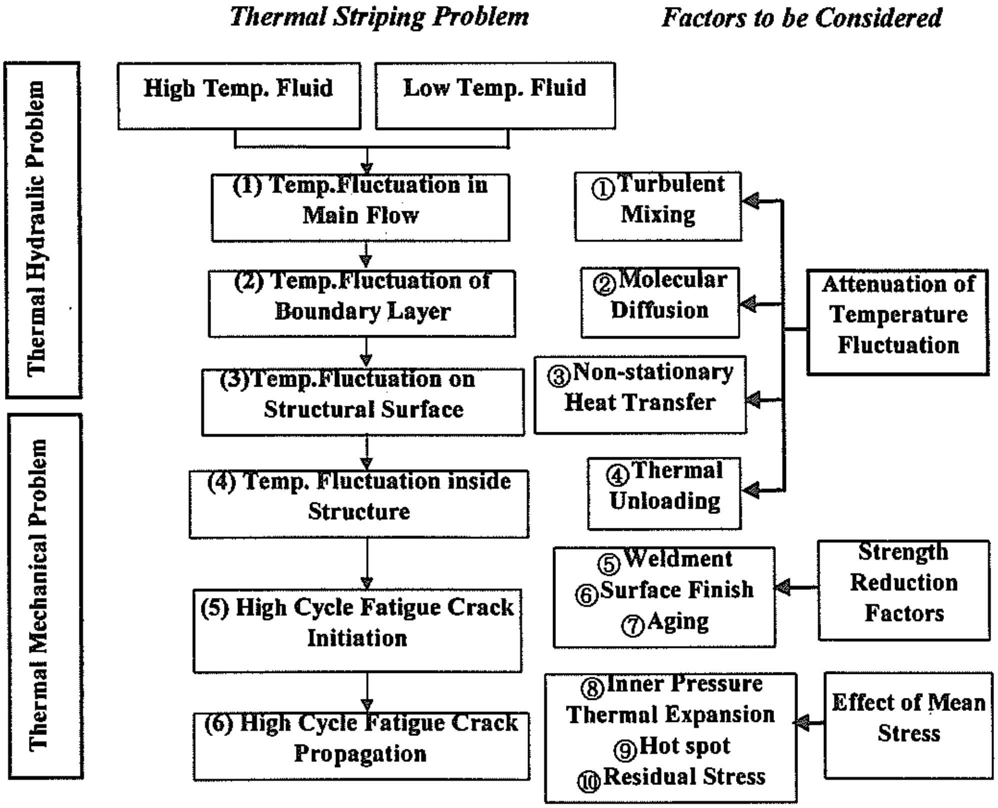

Fig. 2 Mechanism of thermal striping phenomenon and sensitive factors

2.2 Evaluation procedure of thermal striping problem

Considering the mechanism of thermal striping phenomenon shown in Fig.2, thermomechanical analysis was conducted by the procedure shown in Fig.3 with computer codes. For calculation of steps (1) through (4), results of thermal hydraulic analysis are input to thermal mechanical models as thermal boundary conditions by two ways.

One is direct input of temperature distributions in structure obtained by heat conduction code BEMSET[2] into thermal stress analysis models of FINAS code[3]. Advantage of this method is to avoid assumption of heat transfer coefficient on the metal surface, since the BEMSET code can be coupled with the thermal hydraulic code DINUS-3[2] based on heat flux at the structural surface. Disadvantage is that its technique requires coincidence of computational models between the BEMSET and the FINAS codes, however, both models have sometimes different geometry.

The alternative way is prepared for such cases. Fluid temperatures obtained by a DINUS-3 calculation are transferred to the heat conduction models of the FINAS code by using an adjusted heat transfer coefficient which can be evaluated through comparison with calculated results by the BEMSET code. As for steps (5) through (6), two dimensional solid element calculation is carried out by using the FINAS code to evaluate strength reduction factors at a circumferential weld.

For consideration of mean stress induced by the presence of hot/cold spots, 3D shell analysis is also adopted under thermal loads obtained by a coupled calculation by AQUA[2] and BEMSET codes.

Finally, fracture mechanics analysis is conducted by CANIS code[4] in order to predict crack propagation in step(6).

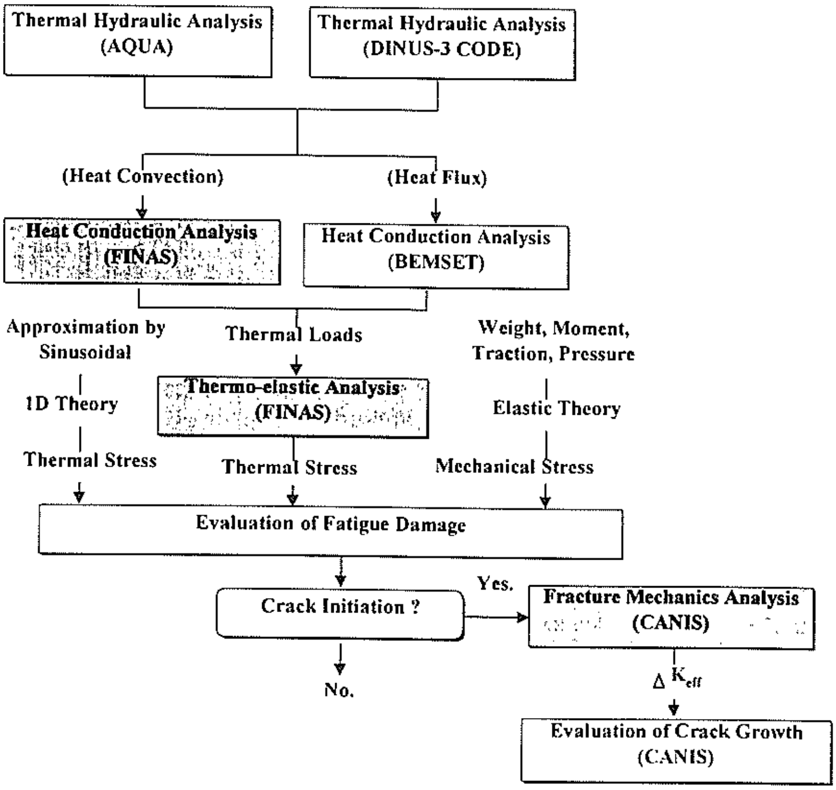

Fig. 3 Evaluation procedure of thermal striping problem with computer codes

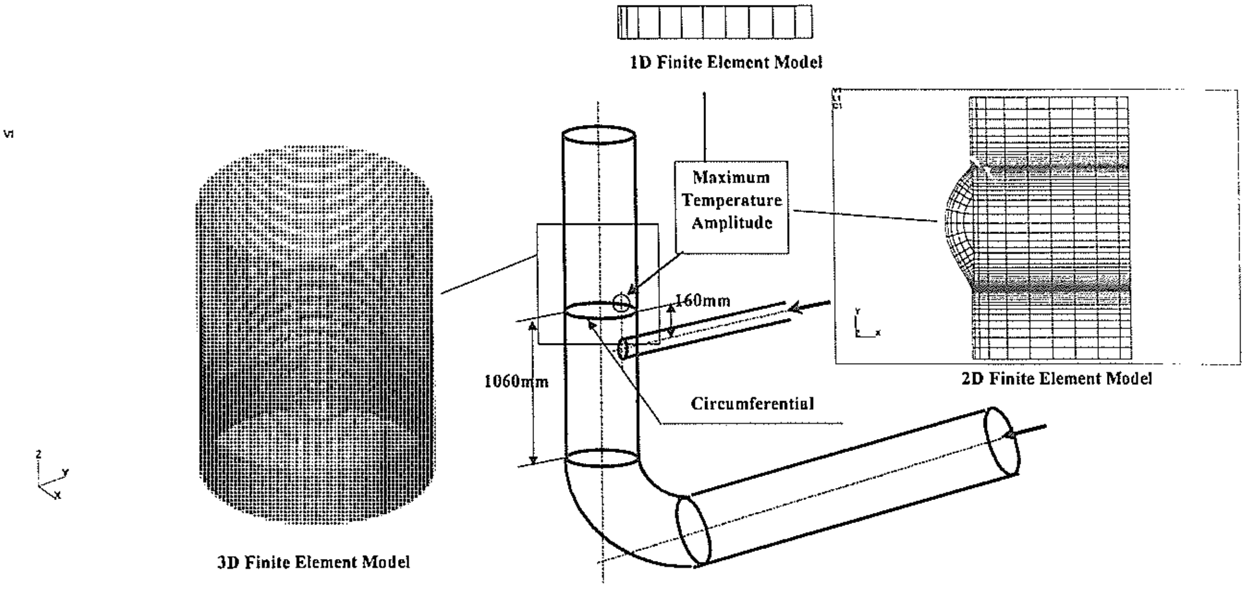

Fig. 4 Finite element models of Phenix secondary pipe

3. Analysis of thermal stress fluctuation

Thermal elastic calculation was carried out by an one dimensional finite element model in Fig.4 using structural temperature distributions obtained by the BEMSET calculation. 8-Nodes quadrilateral axisymmetric elements QAX8 of the FINAS code were utilized for this calculation. Fig.5 shows stress histories on the inner surface of circumferential weld calculated by the FINAS code. The maximum stress value is observed to be 80MPa, however, these 10sec histories do not have periodical characteristics and longer simulation time is desirable.

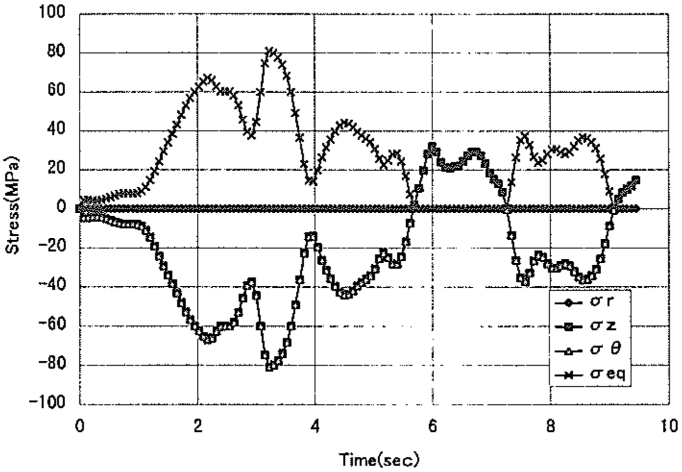

Fig.5 Stress histories at the inner surface of circumferential weld (1-D Analysis)

4. Assessment of crack initiation

4.1 Strength reduction factors

JNC's fatigue evaluation procedure applies strength reduction factors of welded joints that takes into account the effects of metallurgical discontinuity between base and weld metals, geometrical discontinuity at penetration beads and degradation of weld metal[5]. Among these strength reduction factors, geometrical discontinuity becomes dominant in the case of unfinished welded joints subjected to high cycle fatigue. So that, stress concentration factors at welded joint was evaluated by finite element analysis with a 2D finite element model shown also in Fig.4. The geometry of the model was precisely decided from a photograph of the weld bead, and mesh subdivision was determined from sensitivity analysis of stress to mesh size. This model had so different configuration from the model of BEMSET code, that heat conduction analysis was performed by the FINAS code under the heat convection boundary with fluid temperature histories obtained from the DINUS-3 code. A calculated stress contour shown in Fig.6 clarifies that peak stress area is very restricted and plastic strain concentration might not occur since this area is constrained strongly by the surrounded elastic region. Comparing with the 1D calculation result, stress concentration factor K at the weld beads was evaluated to be 2.3. Factor of 1.2 was assumed for surface finish and aging.

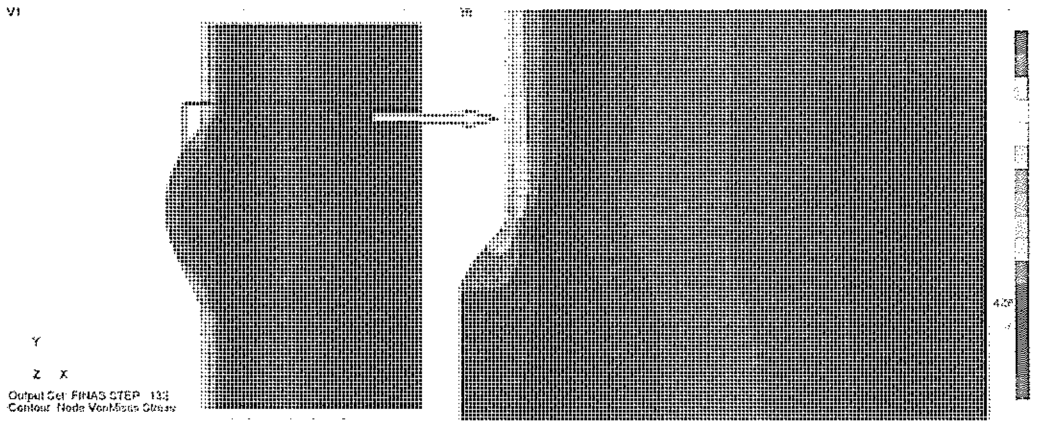

Fig.6 Von Mises stress contour of circumferential weld (3.3sec)

4.2 Mean stress

Mean stress components caused from both mechanical and thermal loads have some effects on fatigue strength and have strong influences on crack propagation rate. Mechanical loads such as axial forces and moments of a piping system were small induced 6.65MPa of mean stress. At the welded joints, residual stress was also considered as 124MPa, which was derived from a yield stress of the material.

As for thermal loading, hot/cold spot causes mean stress by 3-dimensional spatial temperature distributions. 3D finite element analysis was adopted to evaluation by using the shell element QFLA4RT of the FINAS code, which has 9 integral points in wall thickness direction and can consider peak stress on the surface. Time-averaged temperature distribution in the pipe wall obtained from coupled analysis with the BEMSET and AQUA code was input to each integral point of QFLA4RT elements. Fig.7 is a calculated Von Mises stress distribution on the inner surface of the Phenix secondary pipe, where 75MPa of compression stress was generated in transverse direction of the circumferential weld.

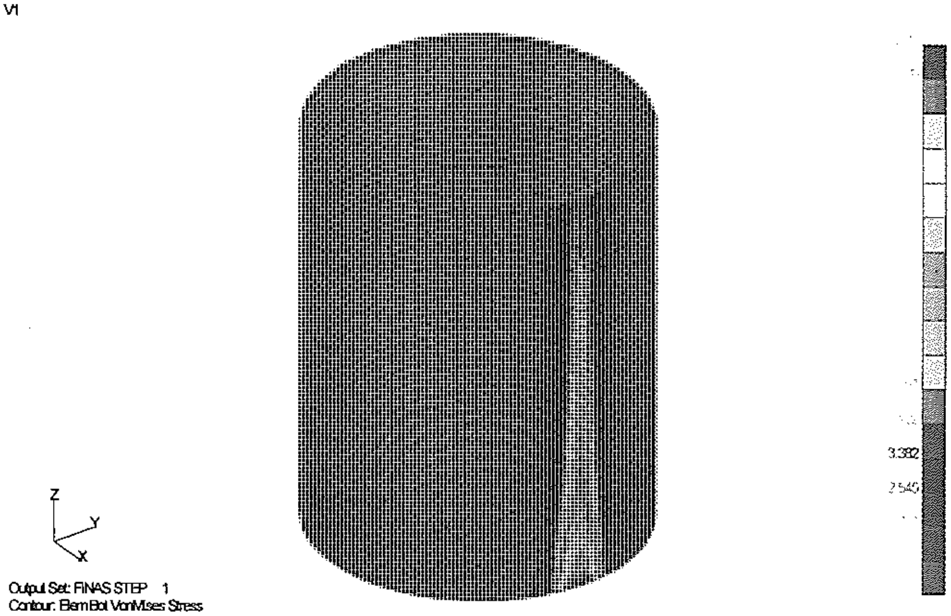

Fig.7 Average Von Mises stress distribution on the inner surface of Phenix secondary pipe

4.3 Fatigue damage

Fatigue damage was calculated from a coupled use of a rain-flow counting method and Miner's rule[6] with 4th order polynomial fitting fatigue curve of the weld joint at 425℃, which was provided in benchmark specification. Strength reduction factors and mean stresses were taken into account by the modified Goodman diagram. Evaluated results of the base metal indicated that stress range was much less than endurance limit (assumed strain range for 10^8 cycle) and crack might not initiate within 90000 hours. On the other hand, crack was predicted to initiate after 3590 hours operation of the reactor at the circumferential welded joint.

5. Crack propagation analysis

5.1 Fracture mechanics analysis with CANIS code

Since the most area of the pipe wall remained in elastic regime, effective range of stress intensity factor K_{eff} was adopted to evaluate fatigue crack propagation considering a closure effect. Stress intensity factor was calculated from a weight function method[7] by using the CANIS code. Based on K_{eff} value, crack propagation rate was estimated by Paris' law and Japanese material data for 304SS (450℃～650℃) [8] without propagation threshold, since technical specification of the benchmark did not provide crack propagation data. Here, initial crack size was postulated to be 0.1mm, which corresponded to fatigue damage D_f=1.0.

5.2 Crack propagation analysis results

Fig.8 shows stress distributions across wall thickness at circumferential weld when simulation time is 3.3 sec, where stress is the maximum at the inner surface and decreases rapidly in the pipe wall. The CANIS code evaluates stress intensity factor based on stress distribution as in Fig.8 at each time step. Fig.9 shows time histories of crack propagation estimated from effective stress intensity factor range and mean stress. In the case of welded joint, crack was predicted to pass through the pipe wall at 10300 hours operation of the reactor.

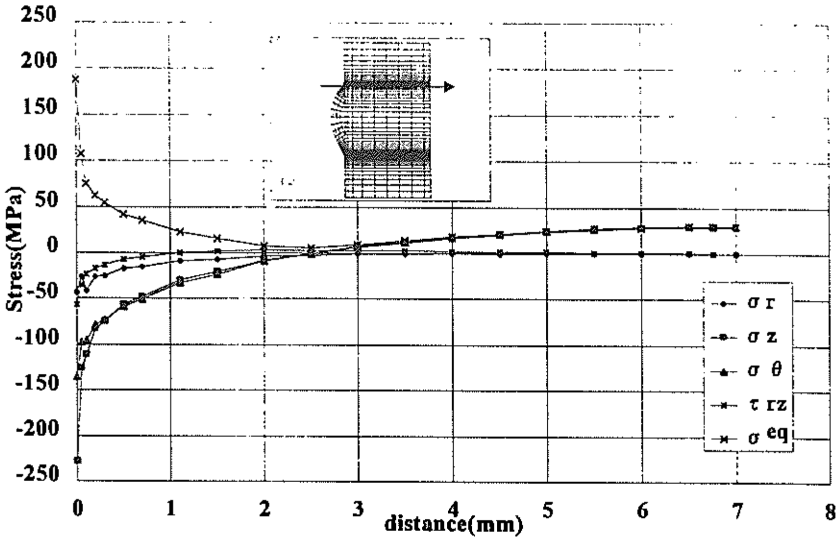

Fig. 8 Stress distribution across wall thickness at circumferential weld (3.3 Sec)

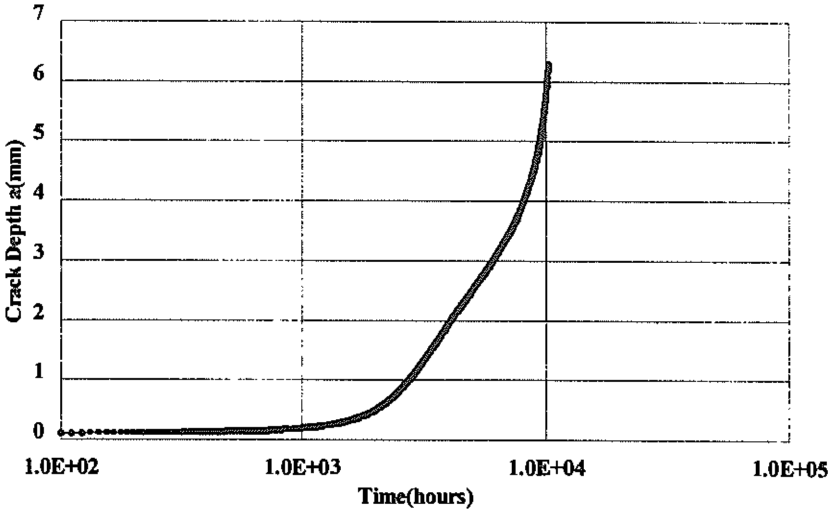

Fig. 9 History of crack growth

6. Conclusion

Under the boundary condition provided from thermohydraulic analysis with DINUS-3, BEMSET, and AQUA codes, possibilities of crack initiation and propagation at the tee junction of the PHENIX secondary circuit due to thermal striping phenomena were assessed. Fatigue damage evaluation results indicated possibility of crack initiation only at the welded joint at 3590 hours operation time.

Since above results, fracture mechanics analysis was carried out for the welded joint. Consequently, it was concluded that crack passed through the pipe wall at 10300 hours operation of the reactor. These results were coincident with plant data as Table 1.

Table 1 Comparison of calculated results with measurements

	Calculated crack initiation time (hr.)	Calculated crack propagation time (hr.)			Calculation at 90000 hr.	Measurements at 90000 hr.
		1mm	3mm	5mm		
Base Metal	∞	———			No crack	No crack
Weld Joint	3590	6379	9757	13079	Through wall crack	Through wall crack

7. Recommendations

For rational evaluation of stress range induced by thermal striping, such attenuation factors of temperature fluctuations are required to be taken into account, as turbulent mixing, molecular diffusion, non-stationary heat transfer, and thermal unloading. To consider these attenuation factors, a coupled simulation of thermomechanical and thermohydraulic is needed. Unfinished welded joints should be avoided from mixing area, since strength reduction factors by geometrical discontinuities are not ignored and are difficult to be evaluated. High cycle fatigue crack propagation is sensitive to mean stress and boundary conditions, therefore sensitivity study is recommended to crack assessment based on Fracture mechanics.

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